NASA/TM—1998-208498 AIAA–98–3736

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November 1998

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Prepared for the
34th Joint Propulsion Conference and Exhibit
cosponsored by AIAA, ASME, SAE, and ASEE
Cleveland, Ohio, July 13–15, 1998

National Aeronautics and
Space Administration

Lewis Research Center

November 1998

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LAUNCH VEHICLE PERFORMANCE WITH SOLID PARTICLE FEED SYSTEMS FOR ATOMIC PROPELLANTS

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SUMMARY

An analysis of launch vehicle Gross Liftoff Weight (GLOW) using high energy density atomic propellants with solid particle feed systems was conducted. The analyses covered several propellant combinations, including atoms of aluminum (Al), boron (B), carbon (C), and hydrogen (H) stored in a solid cryogenic particle, with a cryogenic liquid as the carrier fluid. Several different weight percents (wt%) for the liquid carrier were investigated and the gross lift off weight (GLOW) of the vehicles using the solid particle feed systems were compared with a conventional O_2/H_2 propellant vehicle. The potential benefits and effects of feed systems using solid particles in a liquid cryogenic fluid are discussed.

NOMENCLATURE

A	fixed mass scaling parameter, kg
Al	aluminum
B	boron
B	propellant dependent mass scaling parameter, kg/kg Mp
C	carbon
GLOW	gross lift off weight
H	atomic hydrogen
He	helium
H_2	molecular hydrogen
Isp	specific impulse, s
Mp	propellant mass, kg
NLS	National Launch System
O/F	oxidizer to fuel ratio, or mixture ratio
O_2	oxygen
wt %	weight percent

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INTRODUCTION

New technologies in atom isolation and the physics of material manipulation have led to the discovery and synthesis of materials that can be used as rocket propellants (Refs. 1 through 25). Solid cryogenic propellants storing atoms of Al, B, C, and H, or other atomic additives, require a unique propulsion system design where the fuels are stored at liquid helium (He) temperatures during ground handling and flight. Feeding atomic propellants from a propellant tank through a feed system to a rocket engine will be a formidable challenge.

There are very extensive potential benefits for using atomic propellants. Figure 1 shows the GLOW reductions with atomic hydrogen as a launch vehicle propellant for several atom loadings. With atomic hydrogen at an Isp value of 750 seconds, the GLOW can be reduced by 44% over the O_2/H_2 baseline case. The baseline case is the National Launch System (NLS) with a specific impulse (Isp) of 430 seconds (Ref. 1). The 750 second atomic H Isp performance level requires a 15-wt% of atomic hydrogen stored in solid H_2. The reduction of the GLOW would result in a significant reduction of the cost of space launch, simplification of the ground support equipment and reduction in the investment in launch facilities.

This paper provides analyses of the rocket engine performance for several atomic propellants, and shows their effect on the GLOW of an Earth to Orbit rocket transportation vehicle. Several concepts for the formation, storage, and transport (i.e., feed systems) for atomic propellants are discussed. Also, analyses of the effects of using solid particle feed systems, and the challenges that must be overcome are presented.

WHY HEDM PROPELLANTS?

The overarching vision for HEDM is to create a propellant combination that has at least the performance of O_2/H_2 (typical of the Space Shuttle, which delivers a specific impulse of 452 seconds, in vacuum) but with a higher overall propellant density. The goal is to reduce the vehicle GLOW, simplify vehicle ground operations, and ultimately reduce the cost of space access. Atomic propellants can theoretically offer an extremely high specific impulse over O_2/H_2 propellants. The high-energy atomic propellant must be formulated very meticulously because they do not occur readily in nature. (Ref. 12, Collins). The atoms in the propellant must be stored in a stabilizing medium, such as a cryogenic solid, so as to inhibit or delay their recombination into molecules. Atomic propellants theoretically deliver very high specific impulse as the atoms recombine, release large amounts of energy, and heat the surrounding medium that is used to stabilize the atoms. Using these propellants is more complex than traditional propellants because of their unique chemistry and atomic interactions. Next generation RLV propulsion systems could perhaps use these propellants consisting of atoms in frozen hydrogen particles, within a cryogenic liquid carrier, such as helium (Ref. 10).

VEHICLE DESIGNS AND FEED SYSTEMS

Calculations of rocket engine performance conducted in the past (Ref. 1 and 11) have considered the atomic hydrogen and other atoms that are stabilized in a solid cryogenic material, such as hydrogen. This solid, however, is not easily fed though a conventional feed system. Previous propulsion studies have considered either a monolithic solid containing the atoms, or a segmented solid, much like the concept of a throttleable or controllable solid rocket motor, with preprogrammed pulse elements, each separated by an inhibitor layer. While this may be a viable approach is some cases, the potential for the atoms remaining in a cryogenic atomic state is questionable. As the grain is exposed to the combustion environment, it's temperature goes up quickly, and the ability of the remaining propellant to remain in the atomic state drops dramatically. Isolation of the remaining propellant is needed to have the propellant remain in the atomic state at very low cryogenic temperature, where its energy is not released prematurely. A very light weight inhibitor, or other method of propellant conditioning would be needed. A premature release of the atom recombination energy will result in extremely high thrust, high acceleration, or explosion of the vehicle.

Solid particle feed systems can alleviate the problems of a monolithic solid fuel grain. The analyses presented here illustrate the possible designs for launch vehicles using these feed systems. A two-stage vehicle was analyzed with the solid particle feed systems. Comparisons of the NLS design and GLOW (Ref. 1, 10) with the analyses of two-stage atomic Al, B, C, and H rockets was conducted. These comparisons will show the effects of the solid particle feed systems on GLOW of the vehicles. The vehicle mass is estimated using the traditional mass scaling relation:

$$Mdry = A + B \cdot Mp$$

where:

Mdry	vehicle dry mass, kg
A	fixed mass scaling parameter, kg
B	propellant dependent mass scaling parameter, kg/kg Mp
Mp	propellant mass, kg

Each of these parameters was estimated with detailed tank mass estimation codes, and scaling from existing detailed designs (Ref. 10). The addition of He was also modeled, and all of the mass scaling equations are provided in Tables 1 through 4. The tank maximum operating pressure was 50 psia, the rocket engines used a 30 psia chamber pressure, and we assumed the propellant is pressure fed. In the mission analysis for the atomic rockets, the total velocity change (delta -V) was 9,700 m/s, which is more than 500 m/s higher than the delta-V for the NLS design. This additional delta-V should accommodate any performance losses or altitude compensation losses incurred with the lower engine chamber pressure. The vehicle diameter was 6.1 meters, and the tankage was cylindrical, with ellipsoidal dome ends.

A slurry or gel of solid hydrogen in liquid helium was considered to control the flow of the atom-solid particle propellants. The CET rocket performance code (Ref. 26) was used to estimate the effects on Isp for the addition of He as a carrier fluid. In general, the effect of the He on the vehicle should be a reduction in the Isp of the rocket, but there is also an increase in the propellant density, in some cases. The Isp drops due to the addition of the inert helium and the density of the propellant increases because the helium is a higher density fluid than the solid hydrogen. The Isp reduction is addressed in the rocket performance section. For the monopropellant atomic hydrogen rockets, the solid H_2 particles (encapsulating the atomic H) using a 40-wt% liquid helium carrier has a density of 0.091 g/cm^3 for the cases that were investigated. The solid hydrogen with the encapsulated atoms has a density of 0.077 g/cm^3, about 15 percent lower density than the solid hydrogen liquid helium slurry or gel.

Propellant Types

Several different atomic species were analyzed as rocket propellants. The aluminum (Al), boron (B), carbon (C), and hydrogen (H) atoms were stored (or encapsulated) in solid hydrogen, and a variety of helium mass loadings were used to investigate the performance changes due to the helium carrier fluid. In some cases, oxygen was used as an oxidizer (as a bipropellant), to improve the performance of the atomic Al rocket propellants. The B, C, and H propellants typically had very high Isp performance, and the addition of O_2 would not increase the Isp values. Adding O_2 to the B, C, and H fuel was investigated however, as an option to reducing the total mass of atomic propellants needed for the Earth to Orbit mission. Reducing the total amount of atomic propellants needed would simplify the ground support equipment at the launch site, and the propellant production facility.

Atom Weight Percent

The atom weight percent (wt%) values are the mass of trapped atoms to the total mass of the atoms and the encapsulating solid H_2. The atom wt% values were selected based on the several criteria. A 5-mole percent (mole%) loading in the solid H_2 was selected based on past experimental results (Ref. 2). Current research has concluded that the maximum atom loading that may be possible in the near term is 5-mole%. The 5-mole% loading is translated to a wt% in Appendix A.

The 5 mole% cases translate into different atom wt% for each propellant. With atomic hydrogen, the value is 2.5 wt%. Based on CET Isp calculations, there is no Isp increase for this atomic fuel over O_2/H_2, thus a higher goal for atom storage must be set. If the Isp of the rocket is lower than O_2/H_2, the GLOW will be increased, and the complexity of the very low temperature cryogenics will not be considered worthwhile investment for a less than attractive Isp value.

The Isp performance for the atomic monopropellants is much more attractive at higher atom wt% values. With B and C, the Isp performance is more attractive: 689 seconds for B (at 60 wt%), and 733 seconds for C (at 60 wt%). Atomic H delivers an Isp value of 750 seconds (at 15 wt%). An atomic Al rocket engine will deliver a low Isp at less than 390 seconds (at 80 wt%), and seems to be unattractive.

The remaining cases that were analyzed include either the theoretical peak specific impulses of the propellant combinations, or Isp values where the GLOW of the atomic propellant vehicles was comparable to or lower than the O_2/H_2 vehicle GLOW. Many of these atom loadings are very high: 50 to 60 wt%. While these atom loadings are high compared to the near term practical maximum levels noted earlier (the 5 molar%), they are nonetheless interesting cases, and represent the ultimate goals that should be pursued for successful use of atomic propellants in rocket propulsion systems.

Atomic Propellant Densities

The overall density for the atomic propellants is computed using the equations in Appendix B. Tables 5 to 20 shows the propellant densities for the combinations used in the analyses. The fuel densities are dependent upon the mass fraction of atoms stored and the amount of helium carrier fluid used. The densities of the atom-solid H2 combinations (without He) varied from 0.077 g/cm^3 (15-wt% H in H_2, Table 18) to 149.73 g/cm^3 (50-wt% Al in H_2, Table 6). The analyses using a He carrier fluid were conducted with 10, 20, and 40-wt% of He. The 40-wt% He cases represent a mixture of 70-volume% of the atom-solid (H/H2) combination, with 30-volume% He. This value was chosen as the maximum value of volume fraction for the solid H2 in slush hydrogen used in the National Aerospace Plane (NASP) program (Ref. 27). This 30 volume% of liquid carrier was considered the minimum needed for the practical flow of slush H_2.

ATOMIC PROPELLANT ENGINE PERFORMANCE

Several values of wt% of stored atoms are used in the simulations, and the lower values represent wt% judged to be possible with near term technology. A 5 mole% value of atoms stored in a solid H_2 is considered technically feasible in the near term. The mole% is translated to wt% values for this analysis. Table A1 (Appendix A) shows the near term practical values of mole% versus wt% for the four propellants. It will be shown later that to reduce launch vehicle GLOW, much higher values of atom storage will be required.

Tables 5 through 20 show the Isp performance degradation for using a helium carrier fluid to feed the particles to the recombination chamber. The heats of formation used in the CET code for the various atoms are listed in Appendix C. In the cases with low atom mass fractions in the solid H_2 (10 to 15 wt%), the influence of the He is strong, and it significantly reduced Isp performance. At higher atom loadings (50 wt%), the performance degradation is much lower, with a much reduced effect. The reduced Isp is also accompanied by an increase in propellant density with the atomic H. This density increase is also evident with B and C, for their low atom wt% cases: 22 and 24 wt% respectively. At the higher atom wt% values, the density decreases as the He is added. All of the engines operated at a 30 psia chamber pressure with a 60:1 expansion ratio. A 95% engine efficiency on Isp was assumed.

Propellant Mixture Ratios (O/F)

In addition to estimating the rocket Isp for the atomic propellants as monopropellants, the bipropellant Isp performance (with O_2 as the oxidizer) was computed for several cases. These data were generated to illustrate the potential for reducing GLOW by using a higher density oxidizer, rather than a pure monopropellant. Also, if a bipropellant had an attractive performance level, then the production of the atomic fuel could be significantly reduced, thereby simplifying rocket launch operations and reducing the cost and extent of atomic fuel production.

The Isp performances for the atomic fuels with O_2 were also computed with the three levels of He addition: 10, 20 and 40 wt%. These data were also used in the selection of the O/F for the bipropellant cases, as the addition of He did have a strong effect on engine Isp.

Atomic Aluminum

The predicted performance for aluminum is fairly low compared to O_2/H_2. As shown in Figure 2, the peak Isp is 390 s, significantly lower than the 430 s Isp for the O_2/H_2 case. In the engine performance analyses, it was found that atomic Al Isp values were significantly increased with the use of O_2 as an oxidizer. With O_2 as an oxidizer, the Isp values increase and the maximal value is 507 s at an O/F of 0.5, and a 60 wt% of atomic Al. The atoms of aluminum have a high molecular weight (MW), and hence the addition of O_2 reduces the exhaust MW and increases Isp. The Isp performance is still fairly low, however, and was dropped from consideration after performing some GLOW analyses.

Atomic Boron

Boron performance is high, over 600 seconds for many cases. Figure 3 shows the map of Isp values. A peak monopropellant performance of 689 seconds is delivered at a 60-wt% of B atoms. At a 50-wt% atom loading, the Isp value was 651 s. Adding O_2 as an oxidizer did not increase the 50- and 60-wt% atomic B Isp over the monopropellant cases.

At 22-wt%, the Isp does increase with the addition of O_2. In Figure 4, the addition of He to the propellant (at an atom loading of 22-wt%) showed that a peak Isp value occurs at an O/F of 0.5. The monopropellant Isp, sans He, was 436 s, whereas with an O/F at 0.5, the Isp ranged from 530 s (10-wt% He) to 473 s (40-wt% He). Figure 5 shows the effect of He with a 50-wt% B cases. At this high atom loading, the He has only a small effect on the rocket Isp.

Atomic Carbon

The atomic carbon engine performance is also very high, and it's Isp values were 696 seconds for the 50-wt% atomic C case, and 733 s for the 60-wt% case, as shown in Figure 6. As with the atomic B, adding O_2 as an oxidizer will not increase Isp for the high atom wt% cases. The monopropellant performance at a 24-wt% level was 513 s.

Figures 7 and 8 show the influence of He on the atomic C Isp at 24- and 50-wt%, respectively. In the 24-wt% atomic C case, the addition of O_2, in general, decreased engine Isp. At an O/F of 1.0, the Isp is 504 s (10-wt% He) to 471 (40-wt% He). At this O/F value, the Isp reduction due to the addition of He is relatively small compared to other O/F values. This design point may be worth investigating in future launch vehicle optimizations.

Atomic Hydrogen

The performance with atomic H was the highest of any of the cases investigated. It's Isp values range from 600 to nearly 1300 s. In Figure 9, the highest monopropellant performance is 1500 seconds delivered at a 100-wt% of H atoms. It's unlikely that we will be able to store 100-wt% of atomic H, so the lower levels of 10, 15, and 50-wt% were investigated in the GLOW analyses. Adding O_2 as an oxidizer will not increase Isp.

Figure 10 shows the monopropellant performance for atomic H with both equilibrium and frozen flow. There is a potential for the high wt% atomic hydrogen engine cases to act as a frozen flow, instead of an equilibrium flow. Additional analyses of the combustion assuming frozen flow could be conducted, and the reduction in rocket Isp assessed. All of the analyses presented in this paper use equilibrium flow results, and hence may be optimistic for the high atom wt% cases.

The effect of He on Isp was computed for the 10-wt% and the 50-wt% atomic H cases, and is shown in Figures 11 and 12, respectively. In the 10-wt% case, the addition of He always reduced Isp, but the Isp influence seemed smallest at the O/F value of 1.0. As with the atomic C cases, these O/F analyses may be useful in future launch vehicle optimization. With the 50-wt% case, the addition of He reduced the Isp, but its effect was relatively small compared to the 10-wt% case.

GLOW RESULTS AND COMPARISONS

In Figures 13 through 16, the GLOW values of the four atomic propellant launch vehicles are presented. In most cases, the minimum wt% atomic propellant cases (corresponding to 5-mole%) did not produce Isp values high enough to allow a GLOW reduction over O_2/H_2 technology. Several higher atom storage cases were run to determine the minimum Isp needed for allowing a GLOW reduction. The cases included the atom stored in H_2 as a monopropellant and some cases with O_2 as an oxidizer. Additional cases were run to investigate the effect of helium addition at the 10, 20, and 40-wt% levels.

Atomic Aluminum

The cases with atomic Al are very poor performers when compared with O_2/H_2 technology. As a monopropellant, all of the predicted specific impulse values were 390 seconds. Using O_2 as an oxidizer does improve the overall performance level, to nearly 493 to 507 s Isp, but the overall additional mass for the tankage and structure does not allow the vehicle to deliver a GLOW reduction. Figure 13 shows the GLOW comparison for atomic Al with O_2/H_2. Even with the high 493.1 second Isp value (using an O/F of 0.5, and 50-wt% atomic Al), the vehicle GLOW was still greater than the O_2/H_2 vehicle by 27%. Because of its poor performance, this propellant type was dropped from further consideration.

Atomic Boron

Atomic B has a very good chance of reducing the GLOW of the vehicle when compared with O_2/H_2 propellants. The only drawback is that the B atom wt% must be 50 or 60 percent, which is more than double the 22 wt% value. The 22-wt% cases produced a GLOW of 4.85 times that of O2/H2 vehicle. Using a value of 50 and 60-wt% B, the GLOW was reduced significantly: by 40 and 50% respectively

Helium addition had a powerful effect in increasing the GLOW. Figure 14 shows the sensitivity of GLOW to helium addition, with the 22, 50, and 60-wt% B atom cases. The 60 wt% cases were least affected, but the 22 wt% cases produce unusually large GLOW values: up to 43.5 times the GLOW of the O2/H2 case. Clearly the 22-wt% cases will not be attractive for this application. With the 50-wt% cases, the addition of 10-wt% He does not severely affect the vehicle GLOW, but as the He goes up to 40-wt%, the vehicle GLOW is higher than the O_2/H_2 case.

Atomic Carbon

The monopropellant atomic C cases at the 50 and 60-wt% levels had reduced GLOW values over the O_2/H_2 baseline. However, a 24-wt% atomic C case did not produce a GLOW reduction. The GLOW increase for the monopropellant case with no He was 74%.

Figure 15 presents the GLOW results for atomic C. The atomic C cases produced generally higher Isp values that the atomic B cases, and so their predicted GLOW values were less affected by the addition of He. Both the 50 and 60-wt% cases were able to deliver GLOW reductions even after adding the 40-wt% He.

Atomic Hydrogen

Figure 16 illustrates the GLOW values for atomic H. With atomic H, no GLOW reductions were possible until a 15-wt% of atoms were used. At the 10-wt% H level, the atomic H GLOW was 4% greater than the O_2/H_2 baseline. At a 15-wt% level, the GLOW is reduced by 44%. With a 50-wt% atom loading, the GLOW is reduced by 78%.

When adding He to the flow for the 10-wt% Atomic H cases, the GLOW is 22% to 106% higher than the baseline case, as shown in Figure 16. The 15-wt% atomic H cases only exceed the baseline GLOW when the He is at a 40-wt% level. The range of GLOW reduction for the 15-wt% cases was from 37% (with 10-wt% He addition) to a GLOW increase of 6% with the 40-wt% He added. The 50-wt% atomic H cases are almost unaffected by the He addition. The GLOW reduction is 72% over the O_2/H_2 vehicle GLOW, even with the 40-wt% He addition.

DISCUSSION AND OBSERVATIONS

Atomic B demonstrated very high performance and good GLOW reductions over O_2/H_2, but only if the stored atom values are above 50-wt%. Atomic C also demonstrated excellent performance and ability to reduce GLOW over O_2/H_2 vehicles. As with the atomic B cases, the highest GLOW reductions are possible at the higher atom wt% levels: 50- and 60-wt%. The higher atom loadings demonstrated a good insensitivity to He addition, which will be important for any vehicle using a cryogenic solid particle feed system at a 4 K temperature.

With atomic H at a 10-wt% level, no GLOW reductions over O_2/H_2 vehicles were possible. At 15-wt% atomic H, there were very significant GLOW reductions, for all but the 40-wt% He addition case. The 50-wt% atom cases showed a strong insensitivity to He addition.

Mass summaries of the promising atomic C and H vehicle showing their subsystem masses for each of their two stages are provided in Tables 21, and 22, respectively. The atomic C vehicle used a 50-wt% atom loading, and the atomic H vehicle used a 15-wt% atom loading, and no He addition. The masses for the subsystems are generally conservative, especially the structural masses, which are typically 7 percent of the propellant mass. A 20% contingency mass is added to the dry weights of the vehicles as well. This contingency level is conservative, based on past preliminary space vehicle design rules, and it accommodates many design unknowns. The delta-V used for the vehicle sizing is also conservative, at over 9,700 m/s for the trip to low Earth orbit. This higher than usual delta-V value can also accommodate many design unknowns in both dry mass and engine performance.

Very few combustion tests have been conducted with atomic propellants, and therefore it's difficult to predict the exact combustion efficiency. In such a high energy rocket engine, it will be difficult to extract all of the energy noted in the predicted rocket engine Isp. Engine efficiency sensitivity studies should be conducted on all of the cases in this paper.

The selection of H_2 as the solid cryogen for atom storage is very likely. Hydrogen is an excellent rocket propellant, and can add significant energy due to the atom recombination, as well as combustion. Other solid cryogens that have been considered are solid neon and argon. These solids have been used in atom storage experiments, and may be viable candidates is some ground-based applications. Their lower combustion energies and higher molecular weights do not make them as attractive as H_2, but further investigations are warranted, if higher temperature storage of atoms becomes desirable.

The engine and vehicle efficiency is also most strongly influenced by the ability to flow the 4-K temperature fuel to a 2000-K (or higher temperature) engine, while preventing premature atom recombination. The heat transfer between the feed system components, the engine, and the propellant will create a major engineering challenge. During the transfer of the 4-K atom-solid hydrogen-helium slurry or gel, the temperature of the fuel must not vary more than a few degrees. The atoms will begin to recombine if the solid hydrogen softens. Additionally, the engine will be quite hot - about 2000 K temperature in the recombination -combustion chamber for the atomic hydrogen cases. Maintaining the integrity of the frozen hydrogen with the trapped atoms will be difficult, to say the least. Specialized insulation techniques, or other synergistic cooling techniques, to lower the heat flux to the feed system will no doubt have to be developed. Heat transfer investigations will be needed to create a unique and effective highly integrated engine and feed system design.

CONCLUSIONS

Atomic B and C had significant increases in Isp over O_2/H_2. With B and C, the Isp performance was 689 seconds for B (at 60 wt%), and 733 seconds for C (at 60 wt%). Atomic H delivers an Isp value of 750 seconds (at 15 wt%). An atomic Al rocket engine will deliver a low Isp at less than 390 seconds (at 80 wt%). This low Isp does not reduce the vehicle GLOW, and therefore atomic Al seems to be an unattractive propellant.

Atomic H delivers that highest possible Isp increases, but the propellant must be stored at least a 15-wt% level to deliver a significant GLOW reduction over O_2/H_2.

Several values of wt% of stored atoms were investigated, and the lowest values noted represent the wt% judged to be possible with near term technology. A 5 mole% value of atoms stored in a solid cryogen, such as H_2, is considered technically feasible in the near term. However, to deliver a reduction in vehicle GLOW, much higher values of atom storage will be required.

The GLOW of launch vehicles using atomic B, C, and H was significantly reduced over that for O_2/H_2 propellants. Atomic B reduced GLOW by 12 to 50% at a 60-wt% atom level. Atomic C allowed GLOW reductions of 8 to

48% (at a 50-wt% level) and atomic H the predicted GLOW savings is up to 44% at a 15-wt% atom level, and up to 78% with a 50-wt% of atom storage. Adding He to the fuel to create a gel or slurry with the solid H_2 particles does reduce rocket Isp, but the overall effect is small at the highest atom wt% values.

CONCLUDING REMARKS

Atomic Al did not have any significant performance increase over O_2/H_2, and hence the GLOW for these vehicles was very high. The atomic Al cases were not investigated extensively, but their performance may prove useful in very high density applications.

Helium addition to the atomic fuels reduced performance, but the performance effects were very small for high atom mass fractions: above 60 wt%. At the lower atom loadings of 50-wt%, the He addition has a sizable effect, but the atomic vehicle GLOW was still lower than or comparable to the O_2/H_2 vehicle GLOW. Methods of flowing solid H_2 particles with small wt% values of He will therefore be desirable.

Additional analyses can be conducted for atomic Al, B, H, and C, carried in solid hydrogen with liquid helium. In some cases, the density of the combination of atoms and the solid hydrogen may be overestimated, as it is unknown as to what are the exact interactions of the atoms and the solid H_2 once the atoms are stored in the H_2. Therefore, in addition to the using the densities noted for atomic Al, B, and C, a worst-case lowest density assumption of 0.077 g/cm^3 atomic fuel density can be assumed for the different propellants.

Stored atoms in solid hydrogen are the penultimate step in the development of higher performance, higher density propellants. Future vehicle and engine designs using atom-based propellants have the potential to deliver sizable performance improvements over traditional chemical propulsion systems, as well as commercial benefits (Ref. 29). Commercial aspects of the propellants are being addressed in current research programs. The advanced propellants will require longer development times, so they will take a longer time to be commercialized than more traditional propellants. Elements that are related to the propellant feed system technology might be commercialized in the near future. Near term prospects related to these high energy species might be in the following areas: production methods of the atoms or species, the cryogenic feed system components, superinsulation, valves, flow control and flow measurement components, feed lines, cryogenic storage, and leak detection systems.

Atomic propellants, such as B, C, and H, have an enormous potential for high Isp operation, and their pursuit has been a topic of great interest for decades. Recent and continuing advances in the understanding of matter, and the development of new technologies of simulating matter at it's most basic level, and manipulating matter through micro- and nanotechnology will no doubt create a bright and exciting future for atomic propellants.

Appendix A—Specific impulses for 5-mole% atom cases

Table A1.—Weight% values for 5-mole% of atoms in solid H_2

Atom	Weight% (for 5-mole%)	Monopropellant Isp (s)
Al	41.0	less than 400*
B	22.0	436
C	24.0	513
H	2.6	less than 400*

Expansion ratio = 60:1, Chamber pressure = 30 psia.
*Performance not calculated by CET, as the exit temperature is too low to complete the calculation.

Appendix B—Propellant Densities

The overall density for the atomic propellants is computed using the equations below.

$$\text{Density} = \frac{1}{\left((1 - M_{atom}/\text{density solid } H_2) + (M_{atom}/\text{density of atom}) \right)}$$

Or if helium is added:

$$= \frac{1}{\left((1 - M_{atom} - M_{he})/\text{density solid } H_2) + (M_{atom}/\text{density of atom}) + (M_{he}/\text{density of He}) \right)}$$

Where:
M_{atom} = Atom wt% /100
M_{he} = He wt%/100
Density of solid H2 = 0.077 g/cm^3
Density of liquid He = 0.125 g/cm^3
Density of atoms:

Aluminum	2.700 g/cm^3
Boron	2.340 g/cm^3
Carbon	1.800 g/cm^3
Hydrogen	0.077 g/cm^3

Appendix C—CET Heat of Formation Input Data

Table C1.—Heat of Formation for fuel components–All components at 4 K, except O_2, at 90 K

Component	Heat of formation (cal/mole)
Al atom	[a]78,800.0
B atom	[a]135,000.0
C atom	[a]171,300.0
H atom	[a]52,200.0
H_2 (s)	[a]–2,210.0
He (l)	[b]–1,477.8
O_2 (l)	[c]–3,102.0

[a]Ref. 11.
[b]Ref. 28.
[c]Ref. 26.

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TABLE 1.—ATOMIC ALUMINUM MASS SCALING EQUATIONS

He wt%	A, kg	B, kg/kg Mp
50 wt% Atomic Al, O/F = 0.50		
0	11,517.0	0.211136

TABLE 2.—ATOMIC BORON MASS SCALING EQUATIONS

He wt%	A, kg	B, kg/ kg Mp
22 wt% Atomic B, O/F = 0.00		
0	11,934.3	0.293811
10	11,934.3	0.293357
20	11,934.3	0.289915
40	11,934.3	0.283021
22 wt% Atomic B, O/F = 0.50		
00	11,517.0	0.247787
50 wt% Atomic B, O/F = 0.00		
0	11,934.3	0.242283
10	11,934.3	0.244281
20	11,934.3	0.246290
40	11,934.3	0.250301
60 wt% Atomic B, O/F = 0.00		
0	11,934.3	0.222803
10	11,934.3	0.226758
20	11,934.3	0.230708
40	11,934.3	0.238616

TABLE 3.—ATOMIC CARBON MASS SCALING EQUATIONS

He wt%	A, kg	B, kg/kg Mp
24 wt% Atomic C, O/F = 0.00		
0	11,934.3	0.293403
10	11,934.3	0.290286
20	11,934.3	0.287177
40	11,934.3	0.280970
24 wt% Atomic C, O/F = 1.00		
00	11,934.3	0.221568
50 wt% Atomic C, O/F = 0.00		
0	11,934.3	0.243276
10	11,934.3	0.245180
20	11,934.3	0.247086
40	11,934.3	0.250895
60 wt% Atomic C, O/F = 0.00		
0	11,934.3	0.223998
10	11,934.3	0.227831
20	11,934.3	0.231671
40	11,934.3	0.239328

TABLE 4.—ATOMIC HYDROGEN MASS SCALING EQUATIONS

He wt%	A, kg	B, kg/kg Mp
10 wt% Atomic H, O/F = 0.00		
0	11,934.3	0.339661
10	11,934.3	0.331936
20	11,934.3	0.324184
40	11,934.3	0.308675
15 wt% Atomic H, O/F = 0.00		
0	11,934.3	0.339661
10	11,934.3	0.331936
20	11,934.3	0.324184
40	11,934.3	0.308675
50 wt% Atomic H, O/F = 0.00		
0	11,934.3	0.339661
10	11,934.3	0.331936
20	11,934.3	0.324184
40	11,934.3	0.308675

TABLE 5.—ATOMIC ALUMINUM ENGINE PERFORMANCE AND PROPELLANT DENSITY

41 wt% Atomic Al, O/F = 0.5		
He wt%	Fuel density, g/cm^3	Isp (s)
0	0.1280	n/a
10	0.1277	454.8
20	0.1274	441.4
40	0.1268	413.3

TABLE 6.—ATOMIC ALUMINUM ENGINE PERFORMANCE AND PROPELLANT DENSITY

50 wt% Atomic Al, O/F = 0.5		
He wt%	Fuel density, g/cm^3	Isp (s)
0	0.1497	493.1
10	0.1468	479.9
20	0.1440	465.7
40	0.1388	434.0

TABLE 7.—ATOMIC BORON ENGINE PERFORMANCE AND PROPELLANT DENSITY

22 wt% Atomic B, O/F = 0.0		
He wt%	Fuel density, g/cm^3	Isp (s)
0	0.0978	435.5
10	0.1000	411.7
20	0.1023	385.6
40	0.1071	329.6

TABLE 8.—ATOMIC BORON ENGINE PERFORMANCE AND PROPELLANT DENSITY

50 wt% Atomic B, O/F = 0.0		
He wt%	Fuel density, g/cm^3	Isp (s)
0	0.1491	651.2
10	0.1463	624.7
20	0.1436	n/a
40	0.1384	522.3

TABLE 8.—ATOMIC BORON ENGINE PERFORMANCE AND PROPELLANT DENSITY

50 wt% Atomic B, O/F = 0.0		
He wt%	Fuel density, g/cm^3	Isp (s)
0	0.1491	651.2
10	0.1463	624.7
20	0.1436	n/a
40	0.1384	522.3

TABLE 10.—ATOMIC BORON ENGINE PERFORMANCE AND PROPELLANT DENSITY

22 wt% Atomic B, O/F = 0.5		
He wt%	Fuel density, g/cm^3	Isp (s)
0	0.0978	518.9
10	0.1000	502.5
20	0.1023	485.5
40	0.1071	449.1

TABLE 11.—ATOMIC BORON ENGINE PERFORMANCE AND PROPELLANT DENSITY

50 wt% Atomic B, O/F = 0.25		
He wt%	Fuel density, g/cm^3	Isp (s)
0	0.1491	632.0
10	0.1463	614.1
20	0.1436	594.5
40	0.1384	n/a

TABLE 12.—ATOMIC CARBON ENGINE PERFORMANCE AND PROPELLANT DENSITY

24 wt% Atomic C, O/F = 0.0		
He wt%	Fuel density, g/cm^3	Isp (s)
0	0.1000	512.5
10	0.1020	488.0
20	0.1041	462.0
40	0.1087	402.8

TABLE 13.—ATOMIC CARBON ENGINE PERFORMANCE AND PROPELLANT DENSITY

50 wt% Atomic C, O/F = 0.0		
He wt%	Fuel density, g/cm^3	Isp (s)
0	0.1477	696.3
10	0.1451	668.5
20	0.1425	638.3
40	0.1377	570.7

TABLE 14.—ATOMIC CARBON ENGINE PERFORMANCE AND PROPELLANT DENSITY

60 wt% Atomic C, O/F = 0.0		
He wt%	Fuel density, g/cm^3	Isp (s)
0	0.1809	733.4
10	0.1732	712.2
20	0.1660	684.5
40	0.1535	612.5

TABLE 15.—ATOMIC CARBON ENGINE PERFORMANCE AND PROPELLANT DENSITY

24 wt% Atomic C, O/F = 1.0		
He wt%	Fuel density, g/cm^3	Isp (s)
0	0.1000	487.8
10	0.1020	478.2
20	0.1041	468.4
40	0.1087	447.3

TABLE 16.—ATOMIC CARBON ENGINE PERFORMANCE AND PROPELLANT DENSITY

50 wt% Atomic C, O/F = 0.25		
He wt%	Fuel density, g/cm^3	Isp (s)
0	0.1477	644.7
10	0.1451	621.1
20	0.1425	595.9
40	0.1377	539.9

TABLE 17.—ATOMIC HYDROGEN ENGINE PERFORMANCE AND PROPELLANT DENSITY

10 wt% Atomic H, O/F = 0.0		
He wt%	Fuel density, g/cm^3	Isp (s)
0	0.0770	611.8
10	0.0801	583.2
20	0.0834	551.1
40	0.0910	n/a

TABLE 18.—ATOMIC HYDROGEN ENGINE PERFORMANCE AND PROPELLANT DENSITY

15 wt% Atomic H, O/F = 0.0		
He wt%	Fuel density, g/cm^3	Isp (s)
0	0.0770	750.0
10	0.0801	713.4
20	0.0834	674.4
40	0.0910	587.6

TABLE 19.—ATOMIC HYDROGEN ENGINE PERFORMANCE AND PROPELLANT DENSITY

50 wt% Atomic H, O/F = 0.0		
He wt%	Fuel density, g/cm^3	Isp (s)
0	0.0770	1281.5
10	0.0801	1231.1
20	0.0834	1176.2
40	0.0910	1046.0

TABLE 20.—ATOMIC HYDROGEN ENGINE PERFORMANCE AND PROPELLANT DENSITY

50 wt% Atomic H, O/F = 0.25		
He wt%	Fuel density, g/cm^3	Isp (s)
0	0.0770	1156.3
10	0.0801	1112.4
20	0.0834	1065.0
40	0.0910	954.7

TABLE 21.—ATOMIC CARBON LAUNCH VEHICLE MASS SUMMARY

Subsystem	Mass, kg
50 wt% Atomic C, O/F = 0.00	
Payload	95,708
Fairing	7,648
Payload adapter	5,441
Stage 2:	
Tankage	9,717
Thermal control	9,964
Engine and feed system	10,000
Structure	11,758
Residuals and holdup	2,558
Contingency	8,799
Propellant	167,965
Interstage adapter	17,345
Stage 1:	
Tankage	29,012
Thermal control	29,187
Engine and feed system	10,000
Structure	34,704
Residuals and holdup	7,550
Contingency	22,091
Propellant	495,773
Total	975,220

TABLE 22.—ATOMIC HYDROGEN LAUNCH VEHICLE MASS SUMMARY

Subsystem	Mass, kg
50 wt% Atomic C, O/F = 0.00	
Payload	95,708
Fairing	7,648
Payload adapter	5,441
Stage 2:	
Tankage	18,614
Thermal control	14,247
Engine and feed system	10,000
Structure	11.647
Residuals and holdup	2,534
Contingency	11,408
Propellant	166,384
Interstage adapter	18,086
Stage 1:	
Tankage	57,465
Thermal control	43,474
Engine and feed system	10,000
Structure	35,737
Residuals and holdup	7,774
Contingency	30,890
Propellant	510,527
Total	1,057,583

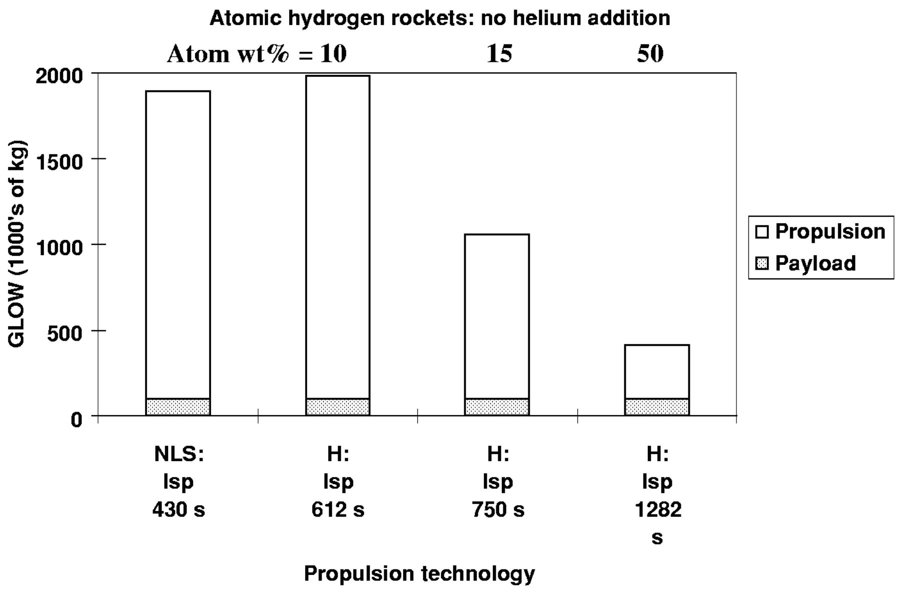

Figure 1.—Atomic hydrogen GLOW: monopropellant H/H2, no helium addition.

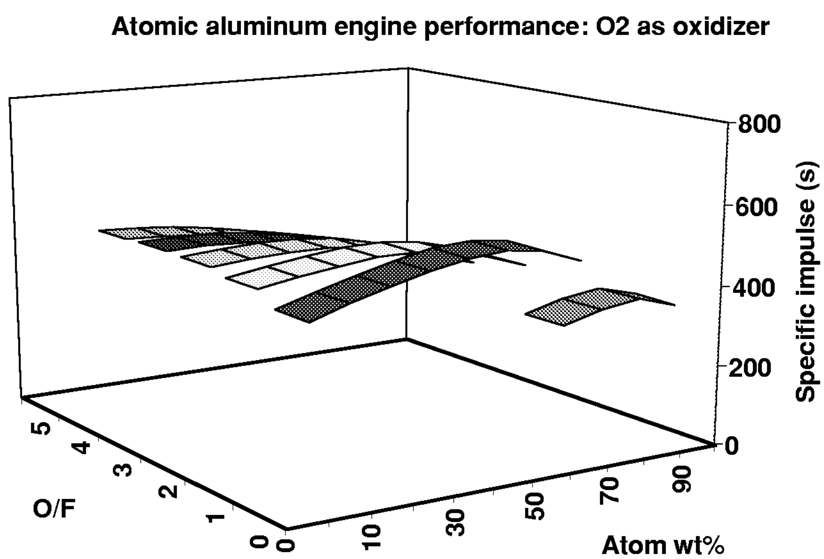

Figure 2.—Atomic aluminum engine performance.

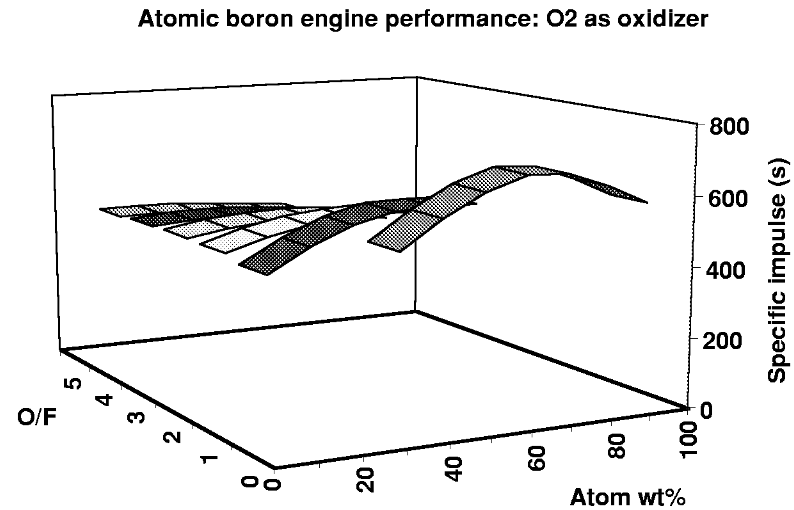

Figure 3.—Atomic boron engine performance.

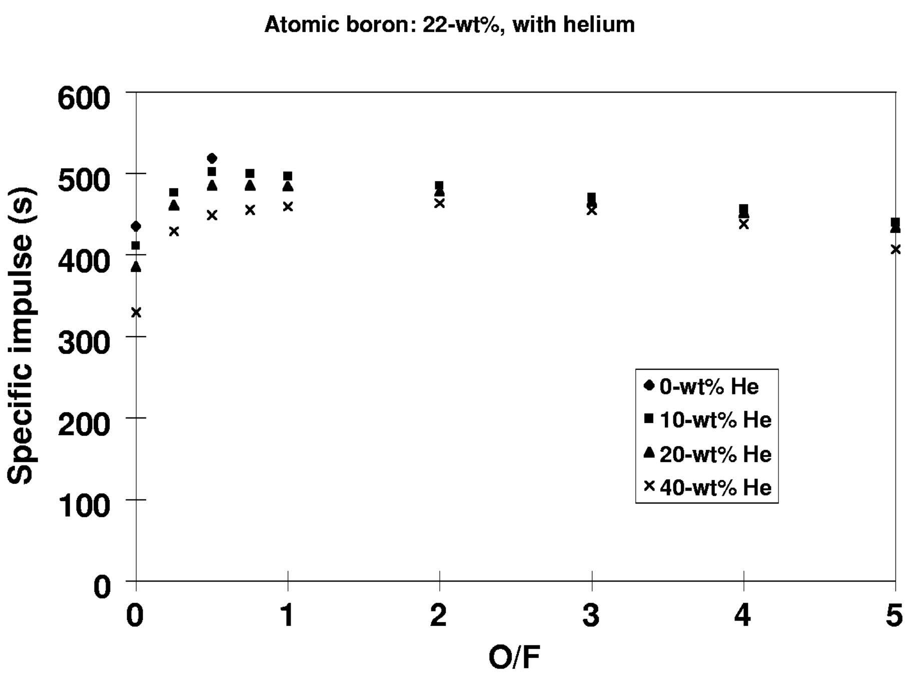

Figure 4.—Atomic aluminum engine performance.

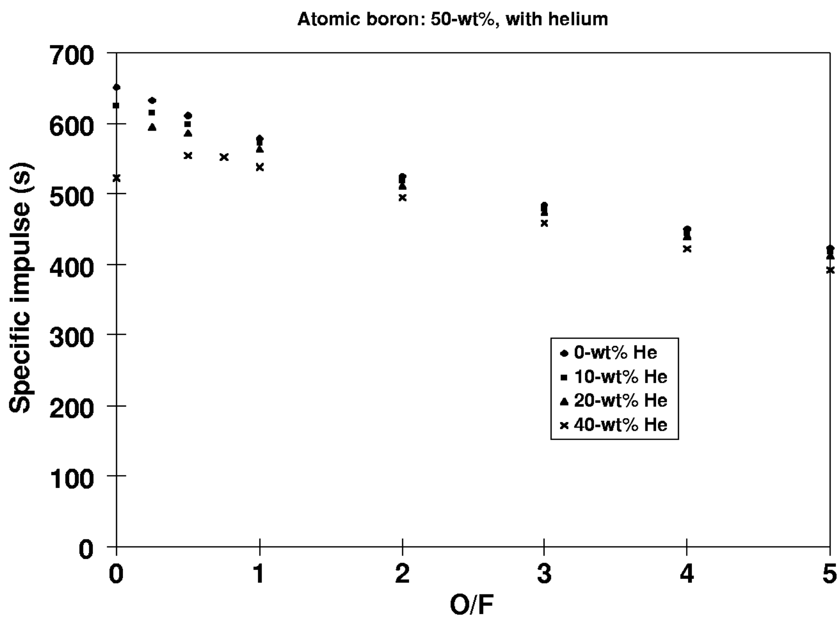

Figure 5.—Atomic boron engine performance.

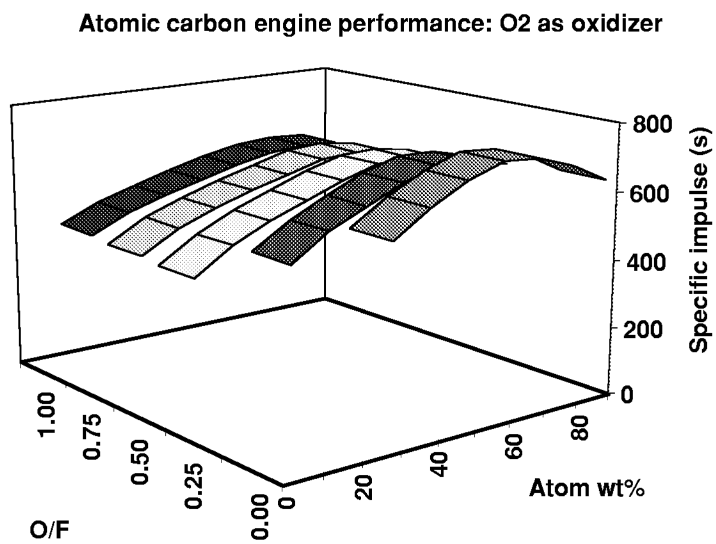

Figure 6.—Atomic carbon engine performance.

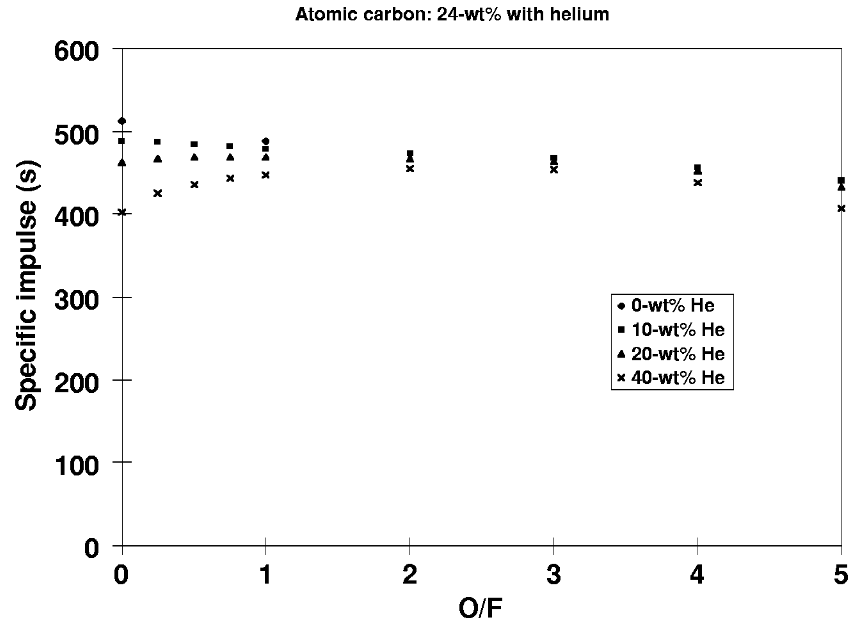

Figure 7.—Atomic carbon engine Isp: helium addition.

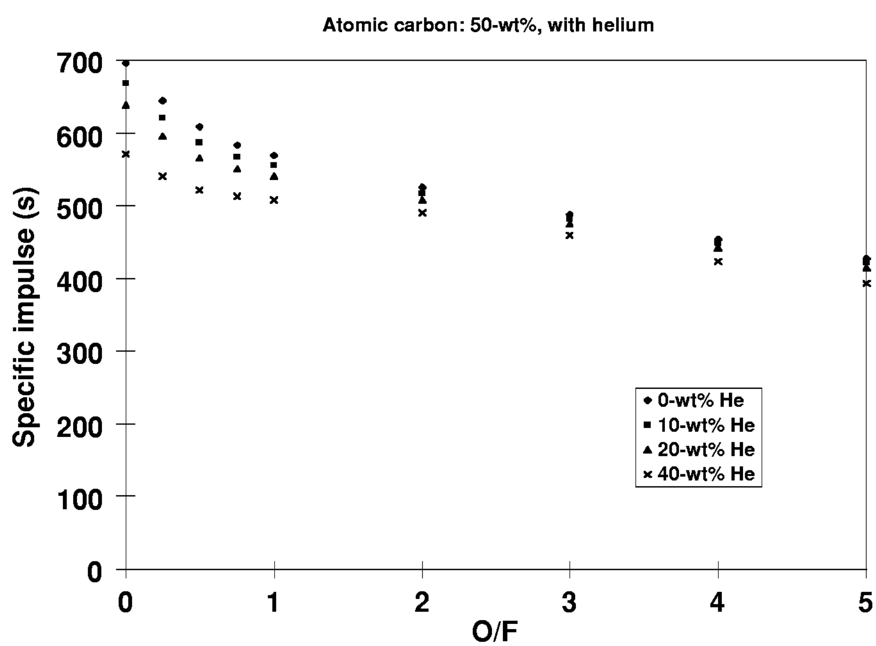

Figure 8.—Atomic carbon engine Isp: helium addition.

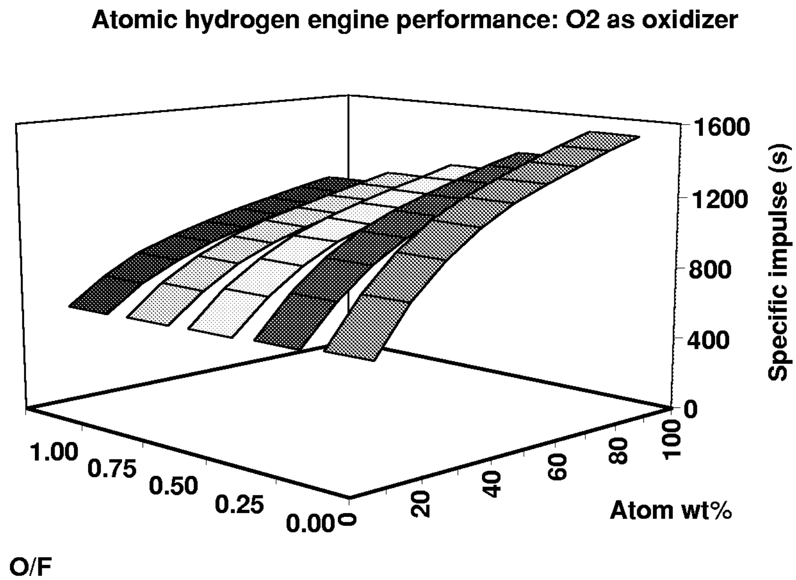

Figure 9.—Atomic hydrogen engine performance.

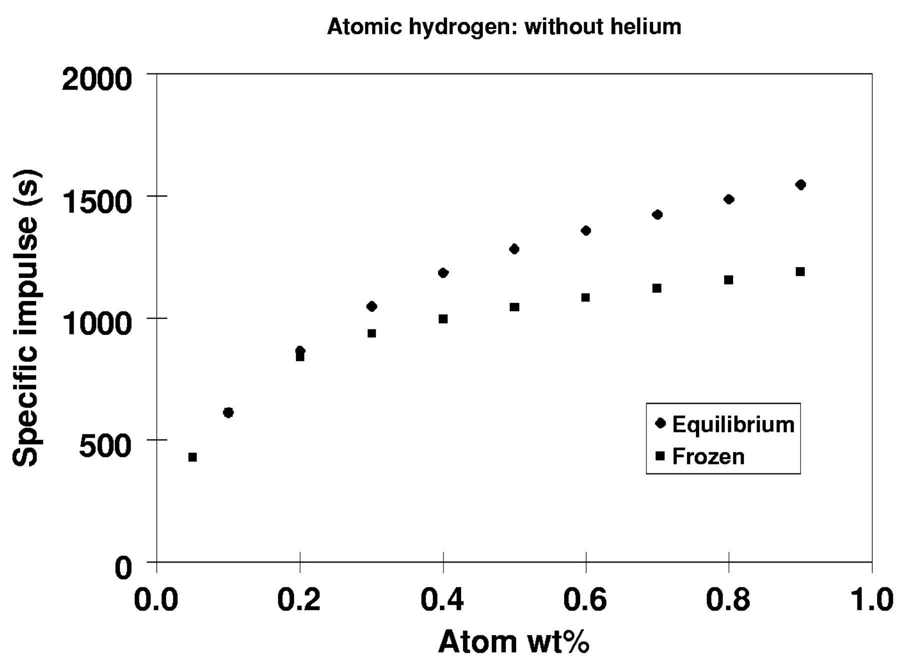

Figure 10.—Atomic hydrogen engine performance.

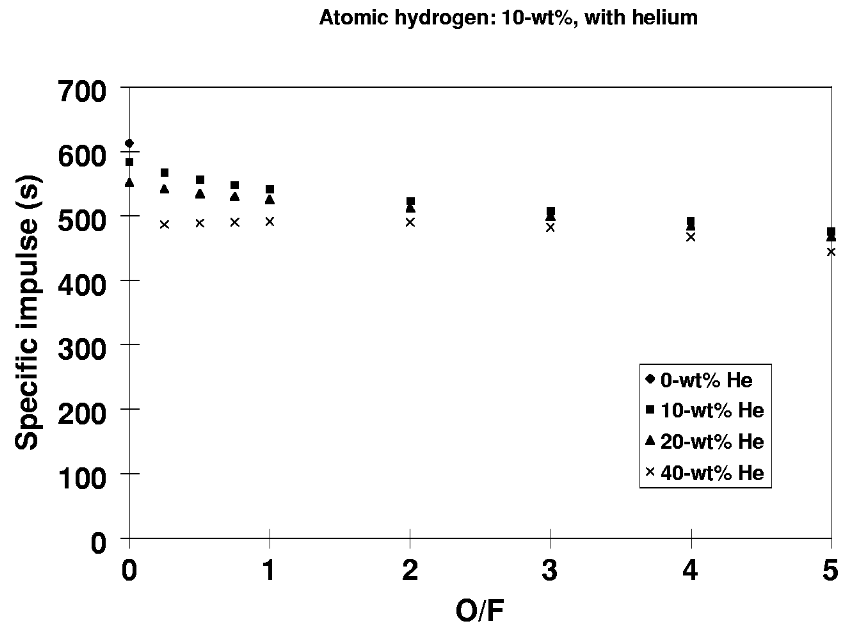

Figure 11.—Atomic hydrogen engine Isp: helium addition.

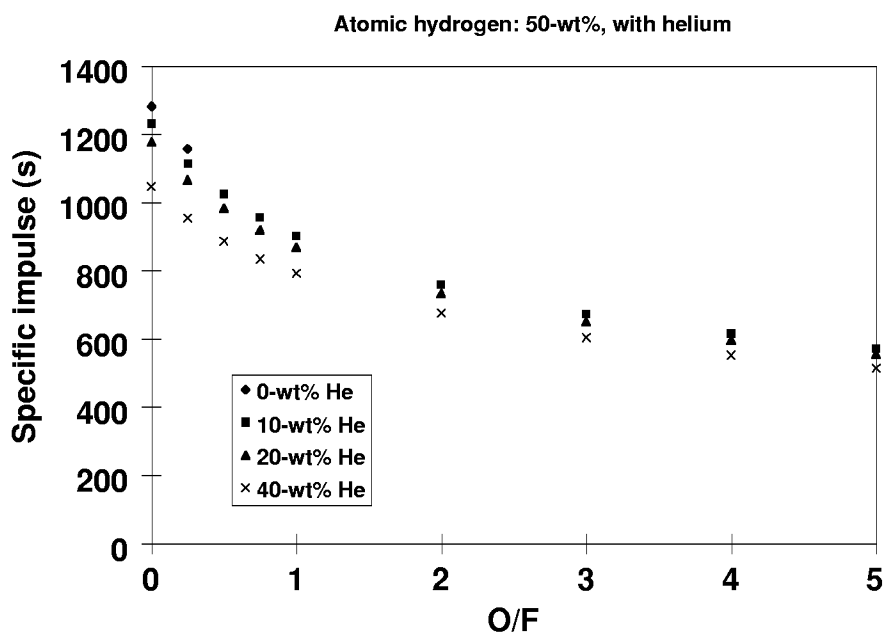

Figure 12.—Atomic hydrogen engine Isp: helium addition.

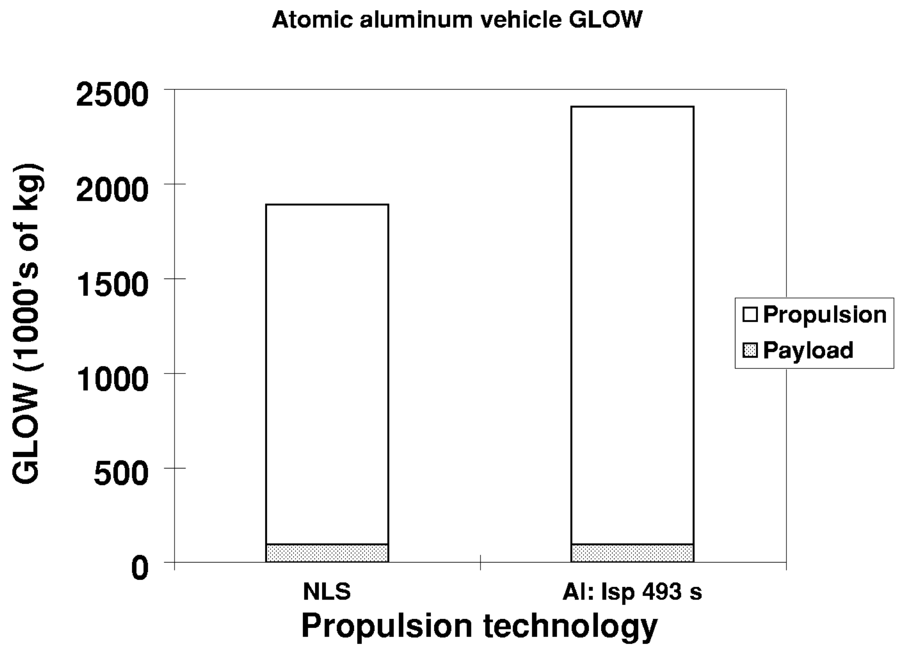

Figure 13.—Atomic aluminum vehicle GLOW.

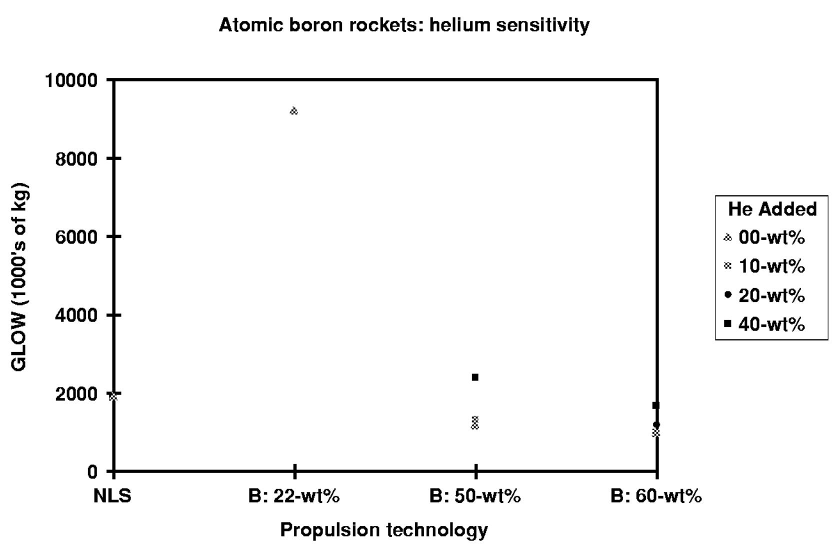

Figure 14.—Atomic boron vehicle GLOW.

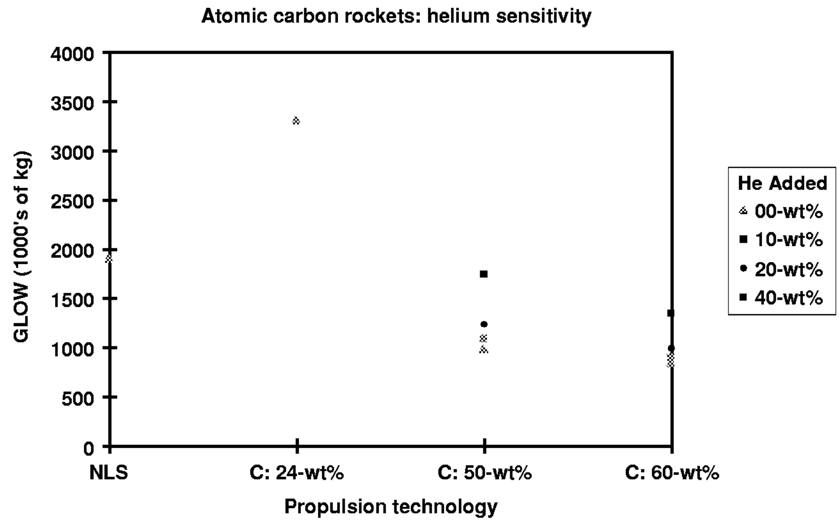

Figure 15.—Atomic carbon vehicle GLOW.

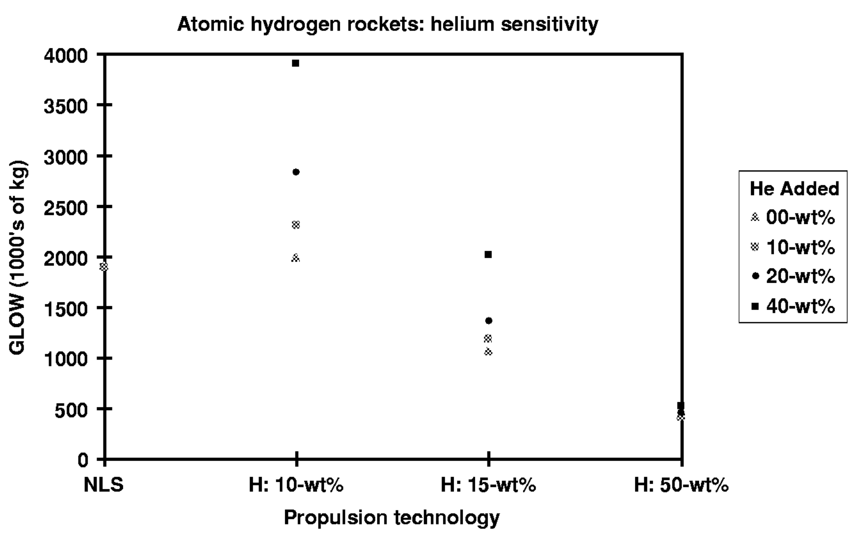

Figure 16.—Atomic hydrogen vehicle GLOW.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
November 1998

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Launch Vehicle Performance With Solid Particle Feed Systems for Atomic Propellants

5. FUNDING NUMBERS
WU–260–98–09–00

6. AUTHOR(S)
Bryan Palaszewski

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–11294

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM—1998-208498
AIAA–98–3736

11. SUPPLEMENTARY NOTES
Prepared for the 34th Joint Propulsion Conference and Exhibit cosponsored by AIAA, ASME, SAE, and ASEE, Cleveland, Ohio, July 13–15, 1998. Responsible person, Bryan Palaszewski, organization code 5830, (216) 977–7493.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Categories: 15 and 20 Distribution: Nonstandard

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13. ABSTRACT ***(Maximum 200 words)***

An analysis of launch vehicle Gross Liftoff Weight (GLOW) using high energy density atomic propellants with solid particle feed systems was conducted. The analyses covered several propellant combinations, including atoms of aluminum (Al), boron (B), carbon (C), and hydrogen (H) stored in a solid cryogenic particle, with a cryogenic liquid as the carrier fluid. Several different weight percents (wt%) for the liquid carrier were investigated and the gross lift off weight (GLOW) of the vehicles using the solid particle feed systems were compared with a conventional O_2/H_2 propellant vehicle. The potential benefits and effects of feed systems using solid particles in a liquid cryogenic fluid are discussed.

14. SUBJECT TERMS
Atomic hydrogen; Cryogenic fuels; Feed systems; Rocket propulsion; Slurry propellants; Gelled propellants

15. NUMBER OF PAGES
28

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	